Response to Interactive comment on "Impact of impurities and cryoconite on the optical properties of the Morteratsch glacier (Swiss Alps)" by Biagio Di Mauro et al.

Anonymous Referee #1

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Authors responses are in *italic,* Reviewer's comments are in **bold.**

The authors used field campaigns and satellite hyperspectral data to investigate the effects of impurities and cryoconite on spectral reflectance of snow and ice. They also conducted lab measurements of optical properties of ice and cryoconite samples, which is related to the impurity content in snow/ice. This study provides a good method to characterize the impact of impurities on snow/ice spectral reflectance by combining field, lab, and satellite measurements, which have an important implication for future study. Before this manuscript can be considered for publication, I have a few comments for the authors to address.

Dear Reviewer #1,

Thank you for the positive evaluation of the manuscript. We have carefully considered each of the Reviewer's comments and suggestions. The Reviewer will find below the responses to the specific comments.

General comments:

1. In the methodology section, the authors provided a detailed description of laboratory, field, and satellite measurement processes, which, however, lacks necessary discussions on the uncertainties associated with these measurements. I suggest that the authors add some discussions on this aspect.

Thank you for this comment. All our measurements feature different uncertainties. Hereafter, the uncertainty related to our measurements is discussed. We will add this information in the Methodology section of the manuscript.

For the gravimetric determination of cryoconite concentration we estimated an error equal to 4% by repeating 5 times the measurement. Regarding EC/OC determination, uncertainty values are estimated from the software of the instrument, and are generally equal to 8-10%; referencing from the manual: "Calculated errors are based on long-term historical data for replicates and instrumental blanks. Over the course of hundreds of replicate runs, the relative standard deviation is typically 5%". For MWAA measurements, the uncertainty is about 10%, and it is given by the squared sum of the uncertainty related to the surface variability of the sample (~5%) and the uncertainty of the optical measurement (calculated as 3 times the variability of the blanks, and equal to 8%).

Regarding ASD data, measurement error is reduced by internally averaging 15 scans for each acquired spectrum, all corrected for the instrument dark current (See Pag. 3 lines 27-28). Field spectra were acquired at midday in clear sky conditions, so the uncertainty related to variability of the incoming radiation should be in principle minimized. Furthermore, three replicas were collected for each sample. We calculated the mean and standard deviation from radiance values and we obtained a coefficient of variation (averaged on VIS-NIR wavelengths) that spans from 1 to 10%. Regarding satellite hyperspectral data, we directly compared Hyperion reflectance with those measured from Landsat and ASD, and we obtained satisfying results. Hyperion reflectance retrievals have been validated several times with independent measurements, also with airborne sensor such as AVIRIS (see for example Kruse et al. 2003). The signal-to-noise ratio (SNR) of Hyperion data varies from 150:1 (for 400-1000 nm) to 60:1 (for 1000-2000 nm); other possible source of uncertainty may come from the atmospheric correction.

Ref:

Kruse, F. A., Boardman, J. W., & Huntington, J. F. (2003). Comparison of airborne hyperspectral data and EO-1 Hyperion for mineral mapping. IEEE Transactions on Geoscience and Remote Sensing, 41(6), 1388-1400.

2. The authors used the characteristic spectral reflectance of clean and dirty snow/ice to infer the effect of impurities in snow/ice. However, both external (e.g., impurity content) and internal (e.g., snow/ice grain properties) factors can affect the spectral reflectance. For example, Liou et al. (2014) showed that snow grain shape and impurity snow mixing structures can significantly influence the effects of impurities on snow albedo. He et al. (2017) further found that snow grain packing also plays a critical role in affecting albedos of both clean and dirty snow. Therefore, such internal factors could potentially affect the interpretation of the spectral observations presented by the authors. It would be informative and useful if the authors could include these recent studies and add some discussions on this issue.

Reference:

He, C., Y. Takano, and K. N. Liou (2017), Close packing effects on clean and dirty snow albedo and associated climatic implications, *Geophys. Res. Lett.*, 44, doi:10.1002/2017GL072916.

Liou, K. N., Y. Takano, C. He, P. Yang, L. R. Leung, Y. Gu, and W. L. Lee (2014): Stochastic parameterization for light absorption by internally mixed BC/dust in snow grains for application to climate models, *J. Geophys. Res.-Atmos.*, 119, doi:10.1002/2014JD021665

We acknowledge that both internal and external factors impact snow and ice spectral reflectance. In particular, internal factors may play an important role in decreasing the reflectance of ice and snow during long and hot summers at mid-latitudes. We will add a brief discussion on these aspects and we will include the suggested papers in the bibliography.

Specific comments:

1. Page 3, Line 29: "The spectra were all obtained around midday under clear-sky conditions." Are there any specific reasons or advantages to obtain spectra in midday with clear sky?

Atmospheric disturbance is an important source of error in field spectroscopy. Incoming radiation in field environment is strongly anisotropic and it is a combination of direct/diffuse sunlight scattered from the sky and adjacent objects. This scattering events produce wavelength-dependent effects. A consequence of this is that HCRF measured in the field is subject to uncertainty introduced by the irradiation environment, and are therefore not only related to properties of the surface (see Milton et al. 2009). For this reason, we measured field spectra in clear sky conditions in order to minimize the uncertainty related to the direct/diffuse ratio during the field measurements. The choice of collecting measurements around midday is motivated by the fact that snow and ice have a strong directional effect (see for example Painter & Dozier 2004), and measuring with the Sun at nadir should minimize this source of error.

Ref:

Milton, E. J., Schaepman, M. E., Anderson, K., Kneubühler, M., & Fox, N. (2009). Progress in field spectroscopy. Remote Sensing of Environment, 113, S92-S109.

Painter, T. H., & Dozier, J. (2004). Measurements of the hemispherical-directional reflectance of snow at fine spectral and angular resolution. Journal of Geophysical Research: Atmospheres, 109(D18).

2. Page 4, Line 4: "solid cryoconite was successively dried at 60◦C for 4 hours". Would this drying process remove some of the organics with relatively high volatility?

We cannot exclude that some compounds with very high volatility may be removed with the drying process, we kept this relatively low temperature in order to avoid sample modifications. In any case, using the Sunset system we observed that organics do not volatilize at temperatures lower than 100°C. With this in mind, if we lost some organics with the drying process, they should be compounds that are in the gas phase at ambient temperature, and that usually constitute a minimum fraction with respect to the total OC.

3. Page 5, Lines 8–12: What is the percentage of total data points used for SVM training and testing set, respectively?

For the two main classes of interest (snow and bare ice), the ratio between training and test set pixel is ~ 10%. We will include this information in the paper.

4. Page 5, Line 30: The indices (narrow- and broad-band) were compared to the impurity concentrations. The indices derived from the Hyperion spectra have a spatial resolution of 30 meters, while the impurity concentration is from point measurement. This is not an apple-to-apple comparison, which may introduce uncertainty. Could the authors discuss this issue?

For this comparison, indices were calculated from the ASD field spectra and not from Hyperion. We will make this point explicit in the new version of the manuscript.

5. Page 6, Lines 28–29: "The only relevant discrepancy . . . where ASD spectra remain almost flat." Are there any possible explanations for this discrepancy at short wavelengths?

We made some hypothesis in line 5-9 (page 9). The observed discrepancy could be due to the presence of contaminated (non-pure) pixels of snow and ice, as previously observed by Negi et al. (2013). Otherwise, it could be related to the presence of meltwater increasing the absorption of solar radiation during the melting season, as observed from airborne hyperspectral reflectance data in other glaciers of the European Alps (Naegeli et al., 2015).

6. Page 7, Section 3.2: The authors only presented the concentration of EC and OC in this section, which seems to lack of the descriptions on the linkage between EC/OC concentration and reduced reflectance. This may confuse the readers. It would be helpful if the authors could explicitly articulate the relationship between EC/OC content and albedo reduction, after the description of EC/OC concentrations in this section.

Unfortunately, this comparison is not possible at the moment. In cryoconite, EC/OC are mixed with a mineral fraction that also reduce the reflectance. In this section, we meant to present the EC/OC concentration data since they can represent an important contribution to the overall albedo reduction. Decoupling the effect of mineral and organic fraction in cryoconite is a very difficult task, and it is out of the scope of the paper. Furthermore, no EC concentration in cryoconite are present in the scientific literature till now. Studying the carbonaceous fraction of cryoconite is an important task in order to estimate the impact of anthropogenic and natural activity on glacier darkening. This is also valid for ice sheets margins, where the "bio-albedo" feedback of cryoconite material has been recently acknowledged (see Cook et al. 2017 The Cryosphere Discuss.).

7. Page 2, Lines 5–10: for the authors' information, a recent study (Lee et al., 2016) combined satellite measurements and model simulations to show the reduced snow albedo caused by impurities over the southern Tibetan Plateau, which could be cited here as a useful reference source.

Reference:

Lee, W. L., K. N. Liou, C. He, S.-C. Liang, Z. Liu, Q. Yue (2016): Impact of absorbing aerosol deposition on snow albedo reduction over the southern

Tibetan Plateau Based on Satellite Observations, Theor. Appl. Climatol., 1-10, 10.1007/s00704-016-1860-4

Thank you for the suggestion, we will add this paper to the bibliography.

Best regards

Biagio Di Mauro & co-authors